Synopsis

Stability is an important criterion in the design and performance of launch vehicles. Present day launch vehicles have become more and more flexible due to the constraints of weight reduction, necessarily imposed for enhanced performance of the vehicle. Due to higher flexibility, the launch vehicle stability becomes a concern. Instability in the launch vehicles has been noticed due to three major sources: thrust, aerodynamic forces and combustion induced instabilities. Instability in the launch vehicles may pose problem to the structural integrity leading to structural failure or it may lead to the deviation in the trajectory of the vehicle. Several structural failures of launch vehicles due to instabilities have been reported in the literature. The prediction of the structural response due to various excitations such as thrust and aerodynamic loading is essential to identify any failure scenarios and to limit the vibrations transmitted to the payload. Therefore, determination of dynamic and stability characteristics of a launch vehicle under the influence of different parameters, is of vital importance.

Disciplines such as, flight mechanics (dynamics), structural dynamics, aerodynamics, propulsion, guidance and control are closely related in the design and analysis of launch vehicles. Typically, flight mechanics, guidance and control problems consider a rigid vehicle for modeling and simulation purposes. The disciplines of structural dynamics and aeroelasticity consider a flexible vehicle. In order to bring in the effect of flexibility on the flight dynamics of the launch vehicle, structural dynamics and aeroelasticity aspects need to be effected. The preliminary design of a new launch vehicle requires inputs from different disciplines and parametric studies are required to finalise the vehicle configuration. The study of the effect of different parameters on the dynamics and stability of launch

vehicles is required. In this context, there is a need to develop an integrated approach that provides tools for the design and analysis of a launch vehicle. The availability of integrated modeling and simulation tools will reduce the requirement of costly prototype development and testing. In the present thesis, an attempt has been made to develop a numerical tool to conduct parametric studies for launch vehicle dynamics and stability. The developed tool is suitable for prediction of onset of instabilities under the influence of different parameters. The approach developed in this thesis is also well suited for specialized analysis of problems involving vertical launch, stage separation, engine shutdown and internal stress wave propagation related to structural integrity.

Stability problems due to thrust and the aerodynamic forces (aeroelastic stability) in the launch vehicles/ missiles have been reported in the literature. Most of these works have modeled the vehicle as a beam or by using discrete degrees of freedom. In these works, the effect of thrust or aerodynamic forces on the flexible body modes is investigated and it is shown that the instability may occur in one of the bending modes due to change in the parameters such as thrust or aerodynamic forces. Traditionally, the dynamic characteristics are obtained in a body-fixed coordinate system, whereas the prediction of trajectory (rigid body dynamics) is carried out in an inertial frame of reference. Only few works have addressed the coupling of the rigid body motion and the flexible body dynamics of a vehicle. But these works also, do not consider the total derivative of displacements with respect to an inertial frame of reference. When the integrated equations of motion are derived in an inertial frame of reference, the rigid body motion and the elastic displacements are highly coupled.

In this thesis, the rigid body motion and the flexible body dynamics is studied in an inertial frame of reference. The flexible body dynamics of the moving vehicle is studied in an inertial frame of reference, including velocity induced curvature effects, which have not been considered so far in the published literature. A detailed mechanics based model is developed to analyze the problem of structural instabilities in launch vehicles. Coupling among the rigid-body modes, the longitudinal vibrational modes and the transverse vibrational modes due to asymmetric lifting-body cross-section are considered.

The model also incorporates the effects of aerodynamic forces and the propulsive thrust of the vehicle. The propulsive thrust is considered as a follower force. The model is one-dimensional, and it can be employed to idealized slender vehicles with complex shapes. The governing differential equations along with the boundary conditions are derived using Extended Hamilton's principle.

Subsequently, the modeling of the propulsive thrust and the aerodynamic forces are included in the formulation. In the literature, the propulsive thrust has generally been modeled as a follower force applied at the nozzle end. Few of the works in the literature have modeled the combustion process in the solid rocket motor and the liquid propellant engine in detail. This is required to understand the combustion induced instabilities. In the present thesis, the propulsive thrust is considered as a follower force and few of the combustion parameters affecting the thrust are considered. In the literature, the modeling of the aerodynamic forces acting on a launch vehicle has been carried out using general purpose computational fluid dynamics (CFD) codes or by using empirical methods. CFD codes are used to obtain the pressure and the shear stress distribution on the vehicle surface by the solution of Navier Stokes/ Euler equations. The empirical methods have been used to obtain the distributed aerodynamic forces acting on the vehicle. The aerodynamic forces are expressed in terms of distributed aerodynamic coefficients. In the present work, the modeling of the aerodynamic forces has been carried out in two different ways: using a CFD package and by using empirical methods.

The stability of a system can be studied by determining the system response with time. Eigenvalue analysis is another tool to investigate the stability of a linear system. To study the stability characteristics of the system using eigenvalue analysis, a computational framework has been developed. For this purpose, the finite element discretization of the system is carried out. Further to that, two different methods are utilized for finite element discretization of the vehicle structure: Fourier Transform based Spectral Finite Element method (SFEM) and an h-p Finite Element method (FEM). The conventional FEM is a versatile tool for modeling complicated structures and to obtain the solution of the system of equations for a variety of forcing functions. The SFEM is more suitable for obtaining the solution for simple 1-D and 2-D structures subjected to shock and transient loads, having high frequency content. In this thesis, the spectral finite element model is developed for a vehicle subjected to the propulsive thrust and the aerodynamic forces. Prediction of instability using SFEM, means solving a non-linear eigenvalue problem. Standard computer codes or routines are not available for solving a non-linear eigenvalue problem. A computer code has been written to solve the non-linear eigenvalue problem using one of the algorithms available in the literature. An h-p finite element model is also developed for launch vehicle. The finite element stiffness and damping matrices due to the thrust, the aerodynamic forces and the rigid body velocity and acceleration are derived using Lagrange's equations of motion. A standard linear eigenvalue problem and a polynomial eigenvalue problem is formulated for determination of instability regimes of the vehicle.

It is important to understand the influence of different parameters such as thrust, velocity, angle of attack etc. on the stability of a launch vehicle. Parametric studies are important during the preliminary design phase of a vehicle to identify the instability regimes. The design parameters can be changed to reduce the possibility of instabilities. Numerical simulations are carried out to determine the unstable regimes of a slender launch vehicle for propulsive thrust and velocity as the parameters, neglecting the aerodynamic forces. Comparison between the results based on a Fourier spectral finite element model and a h-p finite element model are carried out. Phenomenon of static instability (divergence) and dynamic instability (flutter) are observed. Determination of mode shapes of the vehicle is important for deciding the placement of sensors and actuators on the vehicle. In this context, eigenvectors (mode shapes) for different end thrust and speed are analyzed.

Further, numerical simulations are also carried out to determine the instabilities in a slender launch vehicle considering the combined effects of propulsive thrust, aerodynamic forces and mass variation. The finite element model simulation results for aeroelastic effects are compared with the published literature. Stability of a vehicle is analysed for velocity (free stream Mach number) as a parameter, at maximum propulsive thrust, including the effect of aerodynamic forces and mass variation. Phenomenon of static instability (divergence) and dynamic instability (flutter) are observed. With the increase in the

Mach number, branching (splitting) and merging of the modes is observed. At higher Mach numbers, divergence and flutter are observed in different modes simultaneously. Numerical simulations are carried out for a typical nose-cone launch vehicle configuration to analyse the aeroelastic stability at two different Mach numbers using empirical aerodynamic data. The phenomenon of flow separation and re-attachment is observed at the cone-cylinder junction. The stability of a typical vehicle under propulsive thrust and aerodynamic forces is investigated using CFD derived aerodynamic data. The aerodynamic pressure and shear stress distribution for a launch vehicle are obtained from the CFD analysis. The effect of different parameters such as combustion chamber pressure, tip mass and slenderness ratio on the stability of a vehicle is studied.

In the later part of the thesis, solution methodology for the time domain response for a coupled axial and transverse motion of a vehicle is developed. The axial responses (displacements and velocities) of a typical vehicle subjected to axial thrust are determined using direct integration of the equations of motion. The axial displacements due to two different thrust histories are compared. The axial velocities with time at different locations are determined. The time domain and the frequency domain responses for a representative vehicle subjected to a transverse shock force are determined using Spectral Finite Element method (SFEM). The system of equations for a coupled axial and transverse motion of a vehicle is developed. Numerical simulations are carried out to determine the coupled axial and transverse response of a vehicle subjected to axial and transverse forces. The coupling of rigid body motion with the elastic displacements is illustrated.

The thesis is comprised of seven chapters. The first chapter gives a detailed introduction to launch vehicles and covers literature survey of launch vehicle dynamics and stability. The dynamics and stability related aspects of flexible structures are also discussed. In chapter 2, a detailed mathematical model of a slender launch vehicle is developed to analyze the problem of structural instabilities. Chapter 3 deals with the finite element discretization of the vehicle structure using two different methods: Fourier spectral finite element method and an h-p finite element method. In chapters 4 and 5, numerical simulations are carried out to determine the instabilities in a slender launch vehicle considering the effects of propulsive thrust, aerodynamic forces and mass variation. In chapter 6, solution methodology for the time domain response for a coupled axial and transverse motion of a vehicle is developed. The last chapter gives the conclusions and the future scope of work.

To summarize, this thesis is a comprehensive document, that not only describes some detailed mathematical models for launch vehicle stability studies, but also presents the effect of aerodynamic, propulsion and structural loads on the launch vehicle stability. Linear stability analysis of a representative vehicle is carried out for prediction of onset of the instabilities under the influence of different parameters such as velocity, thrust, combustion factors etc. The correlation between the stability analysis and the time domain response is established. In short, the matter presented in this thesis can serve as a useful design aide for those working in the launch vehicle design.